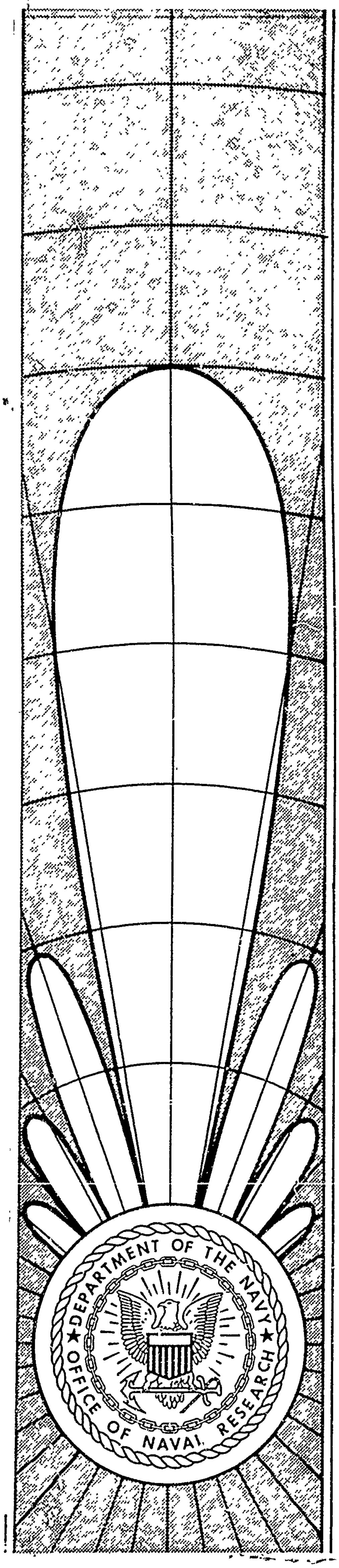

USRL Research Report No. 81
5 May 1966

ANALYSIS OF ACOUSTIC IMPEDANCE DATA

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ANALYSIS OF ACOUSTIC IMPEDANCE DATA

Abstract: Procedures and applicable charts for the analysis of acoustic impedance data obtained from the USRL pulse tube are presented. Formulas and tables for rapid determination of the bilinear transformation $(1 + r)/(1 - r)$ are shown.

INTRODUCTION

The USRL has recently completed development of a system for measuring the complex acoustic impedance and the complex propagation constant of acoustical materials for underwater sound. Basically, the system is an acoustic transmission line 180 cm long with a reversible transducer at one end and a sample of the acoustical material of interest at the opposite end. The operating frequency range is 2.5 to approximately 10 kHz. Hydrostatic pressure is variable to 10,000 psi.

For a sample inserted in the 180-cm-long acoustic transmission line of the system, two quantities are measured at each operating frequency and hydrostatic pressure. These quantities are the magnitude $|r|$ and the phase angle θ of the complex reflection coefficient r at the front boundary of the sample.

This report describes the details of the analysis to be performed on the measured data $|r|$ and θ to calculate the two constants that describe the acoustical behavior of the sample at each discrete frequency and hydrostatic pressure. These are the attenuation constant α (usually expressed in dB/m) and the speed of sound propagation c in the sample.

The basic equation that describes the wave propagation in a sample terminated by a rigid boundary is (see Appendix for derivation)

$$(Z_{in}/Z_T) = (Z_0/Z_T) \coth \gamma d, \tag{1}$$

where Z_{in}/Z_T is the normalized acoustic impedance at the water-to-sample boundary, Z_0/Z_T is the normalized characteristic impedance of the sample, $Z_T = \rho_T c_T$ is the characteristic impedance of water, ρ_T is the density of water, c_T is the speed of sound in water, $\gamma = \alpha + jk$ is the complex propagation constant of the sample, $k = 2\pi f/c$ is the wavenumber in the sample, d is the length of the sample, and f is the frequency.

The ratio Z_0/Z_T in Eq. (1) can be represented by (see Appendix for derivation)

$$\frac{Z_0}{Z_T} = \frac{\rho}{\rho_T} \frac{jk_T}{\alpha + jk}, \tag{2}$$

where $k_T = 2\pi f/c_T$ is the wavenumber in water and ρ is the density of the sample. The measured complex reflection coefficient r for the sound pressure represents an indirect measurement of the water-to-sample boundary impedance according to the relation

$$(Z_{in}/Z_T) = (1 + r)/(1 - r). \tag{3}$$

For brevity, the symbol Z will be used henceforth to represent Z_{in}/Z_T.

When the right-hand terms of Eqs. (2) and (3) are substituted into Eq. (1), the following relation is obtained:

$$\frac{1 + r}{1 - r} = j \frac{\rho}{\rho_T} \frac{k_T d}{(\alpha + jk)d} \coth\,(\alpha + jk)d. \tag{4}$$

In addition to r, the following quantities in this equation are measured: ρ/ρ_T, the ratio of the density of the sample to that of water; and $k_T d$, the acoustic length in radians of a column of water whose length is equal to that of the sample. Thus, when all of the measured quantities are written on the left-hand side, Eq. (4) becomes

$$\frac{1}{(\rho/\rho_T)k_T d} \frac{1 + r}{1 - r} = j \frac{\coth\,(\alpha + jk)d}{(\alpha + jk)d}. \tag{5}$$

Because Eq. (5) is a transcendental equation, it cannot be solved for the unknown values of α and k by algebraic methods. The procedure is to use a chart or family of charts presenting the value of the complex function F for assumed values of the complex independent variable--in this case, $\alpha d + jkd$. Thus F is defined by

$$F = |F|e^{j\phi} = j \frac{\coth\,(\alpha + jk)d}{(\alpha + jk)d}, \tag{6a}$$

and is related to Z by

$$|F|e^{j\phi} = \frac{|Z|e^{j\phi}}{(\rho/\rho_T)k_T d}, \tag{6b}$$

and

$$\tan\phi = \frac{\text{Imag } F}{\text{Real } F} = \frac{\text{Imag } Z}{\text{Real } Z}. \tag{6c}$$

Computations were made on an IBM 1620 computer to evaluate the function F by Eq. (6a) for many values of 2kd and Q, where $Q = kd/2\alpha d$. In these computations 2kd is in radians and Q is derived from a value of $2\alpha d$ in nepers. The computed values $|F|$ and (Imag F)/(Real F), when plotted logarithmically, yield the charts presented in Figs. 1(a) through 1(e). The user enters the appropriate chart through the rectangular coordinates with the measured value, the left-hand side of Eq. (5). The corresponding values of 2kd and Q are read from the curvilinear coordinates. From the values of 2kd and Q, the constants are computed by

$$\alpha = \frac{2kd}{Q}\,\frac{8.686}{4d}\ \text{dB/m}, \tag{7a}$$

$$c = 4\pi df/2kd\ \ \text{m/sec}. \tag{7b}$$

RAPID METHOD FOR THE TRANSFORMATION $(1 + r)/(1 - r)$

The left-hand side of Eq. (5) shows that the measured data (reflection coefficient r) have to be transformed by the expression $(1 + r)/(1 - r)$. The Smith chart of transmission line theory is frequently used for this transformation. In our case, we want the impedance $(1 + r)/(1 - r)$ in the polar form $Z = |Z|e^{j\phi}$. The appropriate chart to obtain impedance in polar form is the modified Smith chart described by Beranek [1].

The result of this r-to-Z transformation is to be used, after division by $(\rho/\rho_T)k_Td$ as in Eq. (6b), in the charts of Fig. 1. The successive use of two separate charts (the modified Smith chart and the charts of Fig. 1) is inadvisable from the point of view of final accuracy. For this reason the r-to-Z transformation should be performed numerically. From the relation

$$Z = (1 + r)/(1 - r), \tag{8}$$

the expressions for $|Z|$ and ϕ are

$$|Z| = \left[\frac{1 + 2|r|\cos\theta + |r|^2}{1 - 2|r|\cos\theta + |r|^2}\right]^{\frac{1}{2}}, \tag{9a}$$

and

$$\tan\phi = \frac{2|r|\sin\theta}{1 - |r|^2}. \tag{9b}$$

Computations by Eqs. (9a) and (9b) are lengthy and laborious. It is possible, however, to modify the equations for simpler computations. The introduction of the auxiliary angle R, defined by $\tan\frac{1}{2}R = |r|$, simplifies Eqs. (9a) and (9b) into

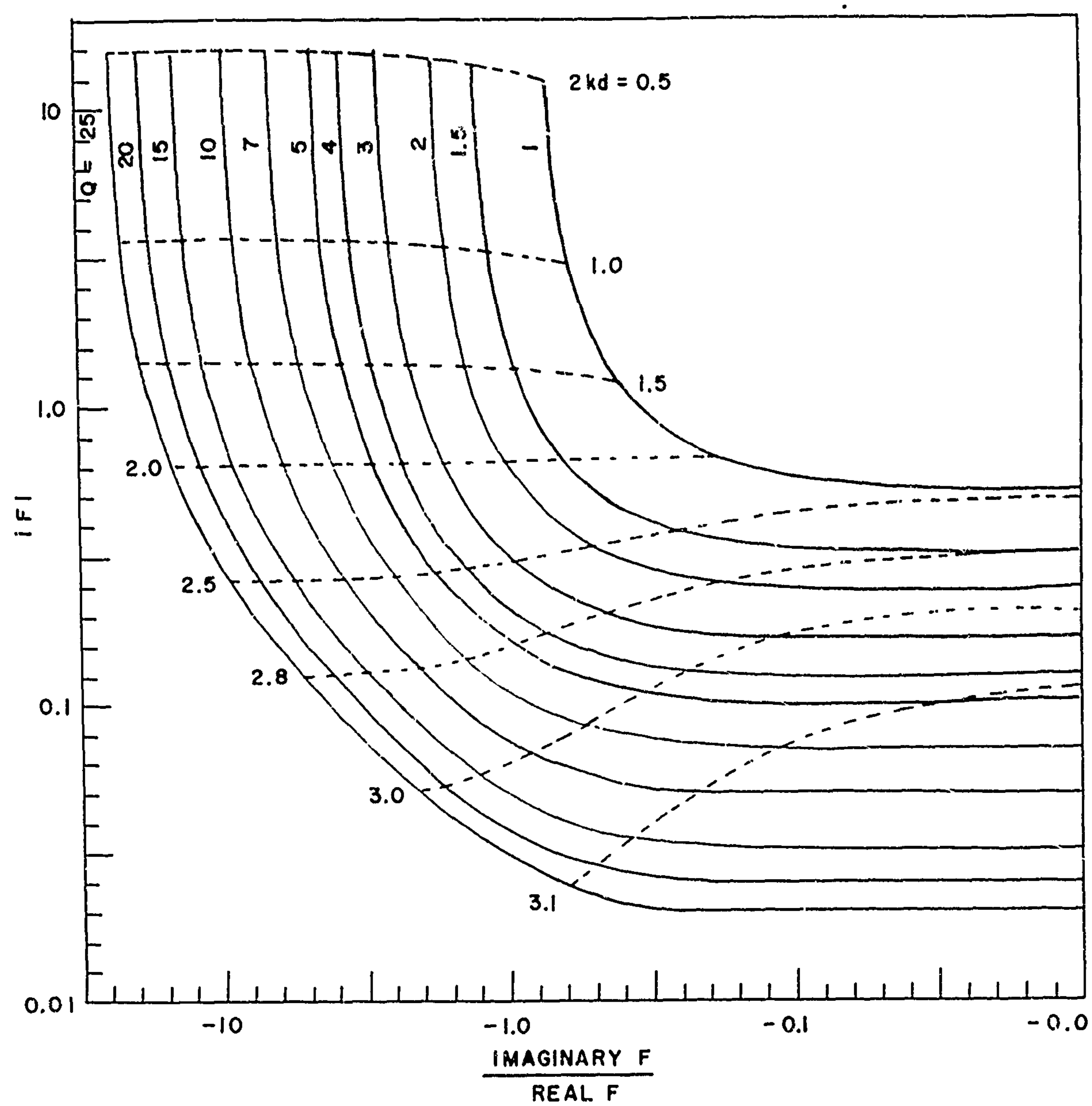

Fig. 1(a). Chart of the computed function

$$F = j\,\frac{\coth\,(\alpha + jk)d}{(\alpha + jk)d}.$$

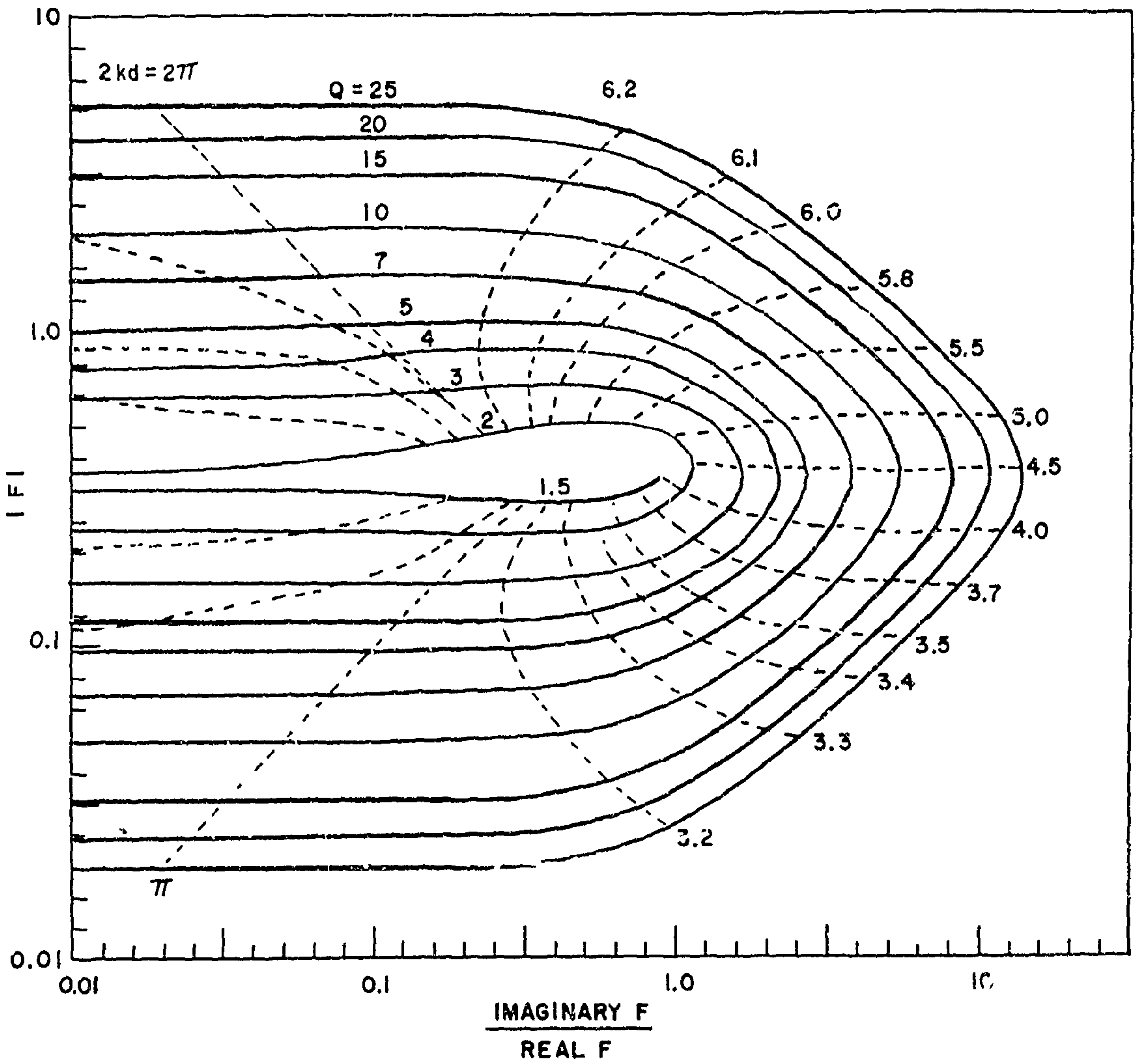

Fig. 1(b). Chart of the computed function

$$F = j \frac{\coth (\alpha + jk)d}{(\alpha + jk)d}.$$

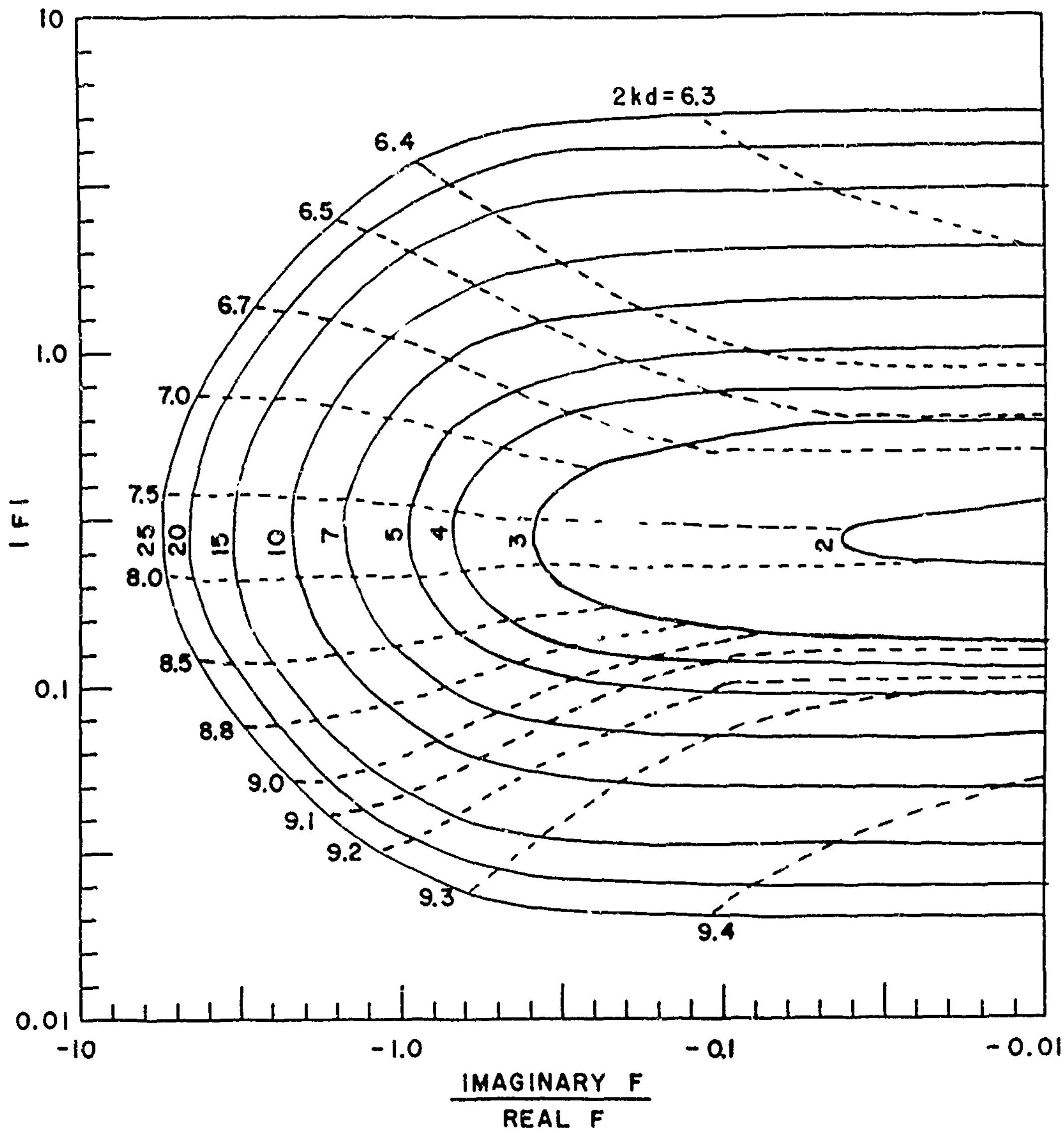

Fig. 1(c). Chart of the computed function

$$F = j \frac{\coth (\alpha + jk)d}{(\alpha + jk)d}.$$

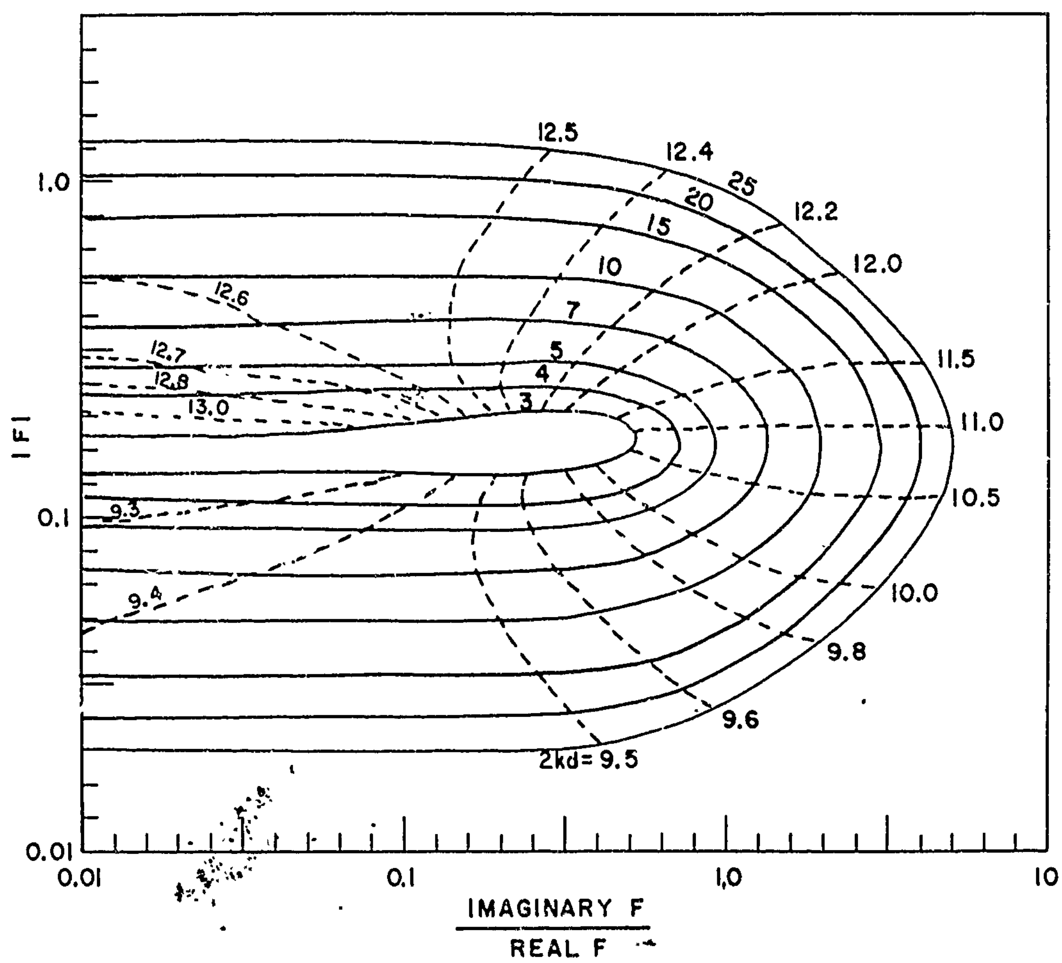

Fig. 1(d). Chart of the computed function

$$F = j \frac{\coth (\alpha + jk)d}{(\alpha + jk)d}.$$

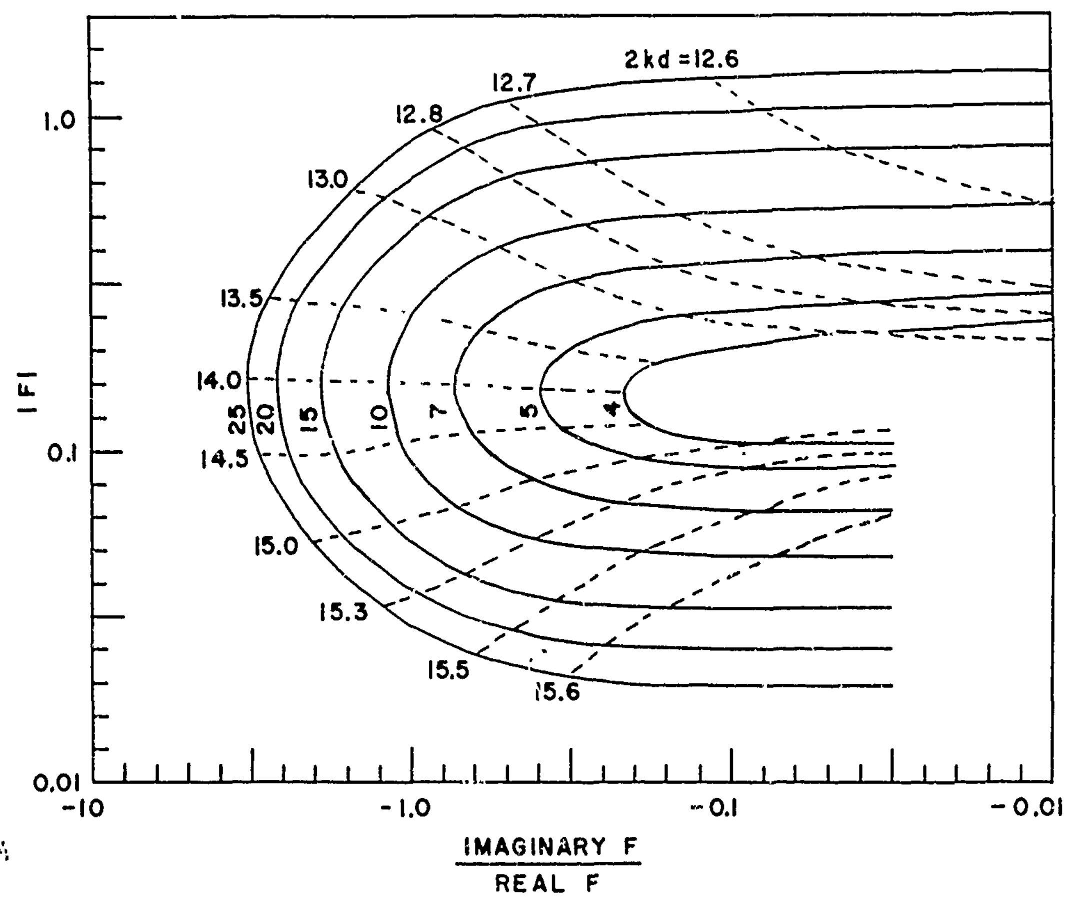

Fig. 1(e). Chart of the computed function

$$F = j\,\frac{\coth(\alpha + jk)d}{(\alpha + jk)d}.$$

$$|Z| = \left[\frac{1 + \sin R \cos \theta}{1 - \sin R \cos \theta}\right]^{\frac{1}{2}}, \tag{10a}$$

and

$$\tan \phi = \tan R \sin \theta. \tag{10b}$$

The auxiliary angle R is always in the first quadrant (because $|r| \leq 1$) and accordingly both sin R and tan R in Eqs. (10a) and (10b) are inherently positive in all cases. Thus, by Eq. (10b), tan ϕ obtains the sign of sin θ; this relation together with the condition that ϕ is restricted to the first or to the fourth quadrant (because $|Z|e^{j\phi}$ physically is a real impedance) defines the specific quadrant of ϕ unambiguously. When θ is in the first or in the second quadrant, ϕ is in the first quadrant; when θ is in the third or in the fourth quadrant, ϕ is in the fourth quadrant.

By regarding $|\sin R \cos \theta|$ as the cosine of another auxiliary angle S, (S restricted to the first quadrant by definition), Eq. (10a) becomes

$$|Z| = \left[\frac{1 + \cos S}{1 - \cos S}\right]^{\frac{1}{2}} = \cot \tfrac{1}{2}S, \text{ if } \sin R \cos \theta \text{ is positive,} \tag{11a}$$

$$|Z| = \left[\frac{1 - \cos S}{1 + \cos S}\right]^{\frac{1}{2}} = \tan \tfrac{1}{2}S, \text{ if } \sin R \cos \theta \text{ is negative.} \tag{11b}$$

It follows from Eqs. (11a) and (11b) that $|Z| > 1$ when θ is in the first or in the fourth quadrants, and $|Z| < 1$ when θ is in the second or in the third quadrants.

Tables I and II are intended for use with Eqs. (10) and (11). Since the rectangular coordinates of the Fig. 1 charts are logarithmic, the tables are also logarithmic to facilitate the plotting of measured data points. In our measurements $|r|$ was measured to the nearest 0.1 dB; for this reason Table I shows values of $|r|$ in the form 20 log $|r|$ in increments of 0.1 dB from -0.1 to -6.0 dB.

A representative example extracted from a series of measurements with the recently developed acoustic-impedance-measuring system will show details of the r-to-Z computations by the method described.

The measured quantities are 20 log $|r|$ = -2.6 dB and θ = 105°. Then,

from trig tables:	$\log \sin \theta = 9.9849$(pos)	$\log \cos \theta = 9.4130$(neg)
From Table I:	<u>$\log \tan R = 0.5174$(pos)</u>	<u>$\log \sin R = 9.9808$(pos)</u>
Add:	$\log \tan \phi = 0.5023$(pos)	$\log \cos S = 9.3938$(neg)
From Table II:	$\log \|Z\| = 9.8901$	
Result:	$\|Z\| = 0.776$, $\tan \phi = 3.18$.	

For clarification it is pointed out that (pos) and (neg) are used above to keep track of the sign of the quantities. For example, log sin θ = 9.9849(pos) indicates that sin θ is positive and log cos θ = 9.4130 (neg) is used to indicate that cos θ is negative.

This completes the r-to-Z computation. To enter the chart, the value of $(\rho/\rho_T)k_T d$, where $k_T d$ is in radians, is needed to compute $|F|$ as in Eq. (6b). In the example being discussed, $\rho/\rho_T = 1.41$ and $k_T d = 2.48$ radians, so $|F| = 0.222$. The chart (Fig. 1(b) is used in this example) is entered through the rectangular coordinates with the values $\tan\phi = 3.18$ and $|F| = 0.222$; Eq. (6c) points out that $\tan\phi$ is (Imag F)/(Real F).

For the precise location of the point that represents $\tan\phi = 3.18$ and $|F| = 0.222$ it must be kept in mind that the charts are logarithmic, hence logarithmic interpolation must be used between the major scale divisions of the charts.

It is equally valid to consider the charts as linear plots of log $|F|$ and log tan ϕ. For this viewpoint the reader needs to visualize that values of log $|F|$ and log tan ϕ can be plotted directly on the chart in a linear fashion. Still for the same example, log tan ϕ = 0.5023(pos) and log $|F|$ = 9.3465(pos); the chart of Fig. 1(b) is entered on the abscissa between 1 and 10 (corresponding to the characteristic 0 of log tan ϕ) at 0.502 of the distance between 1 and 10. For the ordinate on the chart, the entering point is between 0.1 and 1 (corresponding to the characteristic 9 of log $|F|$) at 0.346 of the distance between 0.1 and 1. On the curvilinear coordinates, the plotted point locates the values 2kd = 3.95 and Q = 7. To complete the computation, Eqs. (7) are used to find α and c (d = 0.100 m, f = 6.0 kHz, in this example),

$$\alpha = \frac{(3.95)(8.686)}{7(0.400)} = 12 \text{ dB/m},$$

$$c = \frac{4\pi(0.100)f}{3.95} = 1910 \text{ m/sec}.$$

A few final remarks are probably in order concerning Fig. 1. The charts could have been plotted in any one of several other forms. The form presented was found most expedient for use with our measurements. A possible source of confusion to the reader may be the presence of linear scale divisions on an otherwise logarithmic chart. The example above has attempted to show that the charts may be regarded as logarithmic for tan ϕ and $|F|$ or as linear for log tan ϕ and log $|F|$.

The inquisitive reader is referred to the works of other authors [4-10] for discussions of the mapping of the (coth w)/w and (tanh w)/w functions in connection with a variety of applications in airborne acoustics and in microwave dielectric measurements.

Table I

Computed Values of log tan R and log sin R as a Function of $|r|$

$|r|$ (dB)	log tan R	log sin R
-0.1	1.9386	0.0000
-0.2	1.6377	9.9999
-0.3	1.4616	9.9997
-0.4	1.3366	9.9995
-0.5	1.2396	9.9993
-0.6	1.1603	9.9990
-0.7	1.0932	9.9986
-0.8	1.0351	9.9982
-0.9	0.9838	9.9977
-1.0	0.9378	9.9971
-1.1	0.8962	9.9965
-1.2	0.8582	9.9959
-1.3	0.8232	9.9952
-1.4	0.7908	9.9944
-1.5	0.7606	9.9936
-1.6	0.7322	9.9927
-1.7	0.7056	9.9917
-1.8	0.6804	9.9907
-1.9	0.6566	9.9897
-2.0	0.6339	9.9886
-2.1	0.6124	9.9874
-2.2	0.5918	9.9862
-2.3	0.5720	9.9850
-2.4	0.5531	9.9836
-2.5	0.5349	9.9822
-2.6	0.5174	9.9808
-2.7	0.5005	9.9794
-2.8	0.4842	9.9778
-2.9	0.4684	9.9762

$|r|$ (dB)	log tan R	log sin R
-3.0	0.4531	9.9746
-3.1	0.4383	9.9729
-3.2	0.4239	9.9712
-3.3	0.4099	9.9694
-3.4	0.3963	9.9675
-3.5	0.3831	9.9657
-3.6	0.3701	9.9637
-3.7	0.3576	9.9617
-3.8	0.3453	9.9597
-3.9	0.3333	9.9576
-4.0	0.3215	9.9555
-4.1	0.3100	9.9533
-4.2	0.2988	9.9511
-4.3	0.2877	9.9488
-4.4	0.2769	9.9465
-4.5	0.2663	9.9442
-4.6	0.2559	9.9418
-4.7	0.2457	9.9393
-4.8	0.2357	9.9368
-4.9	0.2258	9.9343
-5.0	0.2161	9.9317
-5.1	0.2066	9.9291
-5.2	0.1972	9.9264
-5.3	0.1879	9.9237
-5.4	0.1788	9.9210
-5.5	0.1698	9.9182
-5.6	0.1609	9.9154
-5.7	0.1522	9.9125
-5.8	0.1436	9.9096
-5.9	0.1350	9.9067
-6.0	0.1266	9.9037

<u>Table II</u>

Tabulation for Finding |Z|

log cos S	log cot ½S	log tan ½S
8.0000	0.0044	9.9956
8.2000	0.0069	9.9931
8.4000	0.0109	9.9891
8.6000	0.0174	9.9826
8.8000	0.0273	9.9727
9.0000	0.0436	9.9564
9.1000	0.0550	9.9450
9.2000	0.0694	9.9306
9.3000	0.0878	9.9122
9.3500	0.0989	9.9011
9.4000	0.1115	9.8885
9.4500	0.1258	9.8742
9.5000	0.1422	9.8578
9.5500	0.1611	9.8389
9.6000	0.1830	9.8170
9.6200	0.1928	9.8072
9.6400	0.2032	9.7968
9.6600	0.2144	9.7856
9.6800	0.2264	9.7736
9.7000	0.2392	9.7608
9.7200	0.2532	9.7468
9.7400	0.2683	9.7317
9.7600	0.2847	9.7153
9.7800	0.3028	9.6972
9.8000	0.3227	9.6773
9.8100	0.3334	9.6666
9.8200	0.3448	9.6552
9.8300	0.3569	9.6431
9.8400	0.3698	9.6302
9.8500	0.3835	9.6165
9.8600	0.3982	9.6018
9.8700	0.4140	9.5860
9.8800	0.4312	9.5688
9.8900	0.4499	9.5501

log cos S	log cot ½S	log tan ½S
9.9000	0.4704	9.5296
9.9050	0.4814	9.5186
9.9100	0.4931	9.5069
9.9150	0.5054	9.4946
9.9200	0.5185	9.4815
9.9250	0.5324	9.4676
9.9300	0.5473	9.4527
9.9350	0.5634	9.4366
9.9400	0.5807	9.4193
9.9450	0.5995	9.4005
9.9500	0.6202	9.3798
9.9550	0.6430	9.3570
9.9600	0.6685	9.3315
9.9620	0.6797	9.3203
9.9640	0.6914	9.3086
9.9660	0.7038	9.2962
9.9680	0.7169	9.2831
9.9700	0.7309	9.2691
9.9720	0.7459	9.2541
9.9740	0.7620	9.2380
9.9760	0.7794	9.2206
9.9780	0.7982	9.2018
9.9800	0.8188	9.1812
9.9810	0.8301	9.1699
9.9820	0.8418	9.1582
9.9830	0.8542	9.1458
9.9840	0.8674	9.1326
9.9850	0.8814	9.1186
9.9860	0.8963	9.1037
9.9870	0.9124	9.0876
9.9880	0.9299	9.0701
9.9890	0.9488	9.0512

log cos S	log cot ½S	log tan ½S
9.9900	0.9694	9.0306
9.9905	0.9806	9.0104
9.9910	0.9922	9.0078
9.9915	1.0047	8.9953
9.9920	1.0179	8.9821
9.9925	1.0319	8.9681
9.9930	1.0469	8.9531
9.9935	1.0630	8.9370
9.9940	1.0803	8.9197
9.9945	1.0992	8.9008
9.9950	1.1199	8.8801
9.9952	1.1288	8.8712
9.9954	1.1380	8.8620
9.9956	1.1477	8.8523
9.9958	1.1578	8.8422
9.9960	1.1684	8.8316
9.9962	1.1795	8.8205
9.9964	1.1913	8.8087
9.9966	1.2037	8.7963
9.9968	1.2168	8.7832
9.9970	1.2308	8.7692
9.9972	1.2458	8.7542
9.9974	1.2619	8.7381
9.9976	1.2793	8.7207
9.9978	1.2982	8.7018
9.9980	1.3189	8.6811
9.9982	1.3418	8.6582
9.9984	1.3674	8.6326
9.9986	1.3953	8.6047
9.9988	1.4298	8.5702
9.9990	1.4694	8.5306
9.9991	1.4923	8.5077
9.9992	1.5178	8.4822
9.9993	1.5469	8.4531
9.9994	1.5803	8.4197
9.9995	1.6199	8.3801
9.9996	1.6684	8.3316
9.9997	1.7308	8.2692
9.9998	1.8188	8.1812
9.9999	1.9694	8.0306

APPENDIX

From transmission line theory, the equation for the input impedance Z_{in} of a line section terminated by an open-circuit (analogous to a rigid boundary--that is, high impedance) is [2]:

$$Z_{in} = Z_0 \coth \gamma d, \tag{A1}$$

where Z_0 and γ are the characteristic impedance and propagation constant, respectively, of the line section, and d is its length. When this line section is used as the termination impedance of another transmission line whose characteristic impedance is Z_T, then Eq. (1) describes the termination impedance normalized to the characteristic impedance Z_T.

Equation (2) can be derived from Eq. (B4) in McSkimin [3], which is

$$Z_0 = j\rho\omega/(\alpha + jk). \tag{A2}$$

When both sides of the equation are divided by Z_T, recalling that $Z_T = \rho_T c_T$, Eq. (A2) becomes

$$\frac{Z_0}{Z_T} = \frac{j\rho\omega}{\rho_T c_T(\alpha + jk)}, \tag{A3}$$

and, since ω/c_T is k_T, Eq. (2) is verified.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Navy Underwater Sound Reference Laboratory P. O. Box 8337 Orlando, Florida 32806	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

ANALYSIS OF ACOUSTIC IMPEDANCE DATA

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

USRL Research Report

5. AUTHOR(S) (Last name, first name, initial)

Sabin, Gerald A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
5 May 1966	14	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	USRL Research Report No. 81
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

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DD FORM 1 JAN 64 1473

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Security Classification

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Acoustic impedance						
Propagation constant						
Acoustical materials						
Underwater sound						
Reflection coefficient						
Test facility						
Mathematical analysis						

INSTRUCTIONS

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